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A COMPARISON BETWEEN PROPOSED SMALL MODULAR REACTORS AND EXISTING POWER REACTORS WITH REGARD TO SPENT FUEL NUCLEAR MATERIAL ATTRACTIVENESS[1]

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ABSTRACT
The nuclear material attractiveness of used fuel from proposed small modular reactors is evaluated relative to used fuel from the existing fleet of power reactors. Irradiated fuels at several burn-ups and cooling times are considered. The methodology for evaluating the materials attractiveness is based on previously used metrics and binning approaches and is consistent with the "attractiveness levels" that are normally reserved for nuclear materials in DOE nuclear facilities.

Commercial power reactor fuels are unattractive at charge but may become attractive after discharge and age, depending upon the degree of burn-up, the fuel composition, and the reactor type. Some used Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) fuels in the US are over 40 years in age and their radiation dose rates continue to decline, calling into question the "self protecting" nature of these older used fuels. This study examines the attractiveness of used fuel assemblies from typical BWR 7x7, BWR 8x8, PWR 17x17, PWR-MOX 17x17, and VVER-440 reactors.

A new generation of small modular reactor (SMR) designs promises a number of benefits relative to the existing fleet of commercial power reactors, including portability, viable initial investment level, scalability due to modularity, and improved security. The somewhat shorter length (and hence lighter weight) of SMR fuel assemblies along with the potential for greater decentralization are additional factors that need to be considered. Like commercial power reactors fuels, the two candidate SMR fuels are unattractive at charge, but may become attractive after discharge and age, depending upon the degree of burn-up, the fuel composition, and the reactor type. For all practical purposes the attractiveness of the used commercial power reactor fuels and used fuels from the two SMRs under consideration in the US are identical. The differences between the existing power reactors and the two proposed SMRs largely comes down to differences in fuel assembly size and facility characteristics.

This study is consistent with previous studies that demonstrate the importance of ensuring that

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adequate safeguards and security measures are in place at all nuclear facilities. This study has been performed at the request of the United States Department of Energy/National Nuclear Security Administration (DOE/NNSA).

INTRODUCTION

This study examines the nuclear material attractiveness of used nuclear fuel from the existing fleet of commercial power reactors and several proposed small modular reactors (SMRs). It expands upon previous studies which have focused primarily on nuclear materials associated with various existing and proposed nuclear fuel cycles that involve or could involve reprocessing/recycling [1,2,3]. Usually, used fuel after reprocessing would lose most of its radioactivity and produce nuclear materials which generally are accounted for as "bulk" (*i.e.*, no defined sizes or shapes). Thus, only the radiation dose rate of the used fuel before processing is relevant to the dose rate portion of the materials attractiveness analysis.

The basic idea of material attractiveness is to classify materials into four categories of weapons utility: preferred materials, potentially usable materials, impractical materials, and impossible materials. These categories and the assigned qualitative attractiveness level (*e.g.*, high, medium, low, and very low) are given in **Table 1** and as shown they can be equated approximately to the attractiveness levels in the DOE graded safeguards table [4].

Table 1. Nuclear Material Attractiveness and Levels, as related to Weapons Utility

Weapons Utility*	Material Attractiveness	Attractiveness Level [4]
Preferred Material	High	~B
Potentially usable, but not preferred material	Medium	~C
Impractical, but not impossible material	Low	~D
Impossible material	Very Low	~E

*Note that a material that is impractical or impossible to process and then fashion into a nuclear explosive device (NED) for the assumed sub-state adversary may still be potentially usable by a state-level adversary.

Power reactor fuels of low-enriched uranium (LEU) are Very Low attractiveness at charge but can become more attractive after discharge and aging because of the plutonium produced in the fuel during irradiation. The attractiveness after discharge and aging will depend upon the degree of burn-up, the fuel composition, the reactor type, and the cooling time (or age).

A new generation of small modular reactor (SMR) designs promises a number of benefits relative to the existing fleet of commercial power reactors, including portability, viable initial investment level, scalability due to modularity, and improved security. The USDOE has supported one reactor type and will support one other integrated PWR (iPWR) based SMRs through its FOA (Funding Opportunity Announcement) program in their application for design certifications from the USNRC. These iPWR based SMRs used partial or half length PWR 17x17 fuel assemblies. Depending on their operating burn-up, the attractiveness of the used fuels from these iPWR based SMRs is assessed and compared with those from the existing power reactors.

METHODOLOGY

Materials attractiveness needs to be considered in three distinct phases in the process to construct a nuclear explosive device (NED): the acquisition phase, processing phase, and utilization phase.

1. In the *acquisition phase*, only properties of the nuclear material that would prevent or deter an adversary from stealing/diverting the material are considered.
2. In the *processing phase*, only properties of the nuclear material that would prevent or deter the adversary from processing the acquired material into a metal or alloy are considered.
3. In the *utilization phase*, only properties of the nuclear material that would prevent or deter an adversary from converting the processed metal or alloy into the desired size and shape and using it in a NED are considered.

When evaluating the attractiveness of used nuclear fuel, the material being handled has a defined size and shape and accordingly has a specific net weight and dose rate associated with it. In the acquisition phase, the net weight and dose rate are important considerations when an adversary of concern (*e.g.*, terrorists) tries to access and acquire the used fuel assemblies. In the processing phase, the form and concentration of the uranium or plutonium in the nuclear material are important considerations in evaluating the difficulty in extracting the uranium or plutonium and converting it to metal. In the utilization phase, the bare critical mass and heat content of the uranium and plutonium metals, extracted from the nuclear material, are important considerations. In a simplified analysis, uranium enrichment is used as a proxy for bare critical mass and plutonium-238 content is used as a proxy for heat content.

In determining the overall material attractiveness level, the attractiveness associated with the factor that is most relevant to the nuclear material in question dominates the materials attractiveness. In other words, the overall material attractiveness is given by the dominant sub-factor that yields the overall lowest attractiveness level. The quantification principles for the attractiveness sub-factors are provided in **Table 2**. In the case of plutonium, any isotopic composition is considered equivalent in attractiveness to Very Highly Enriched Uranium for the Nuclear Material Mass Requirements sub-factor. In the case of uranium, any isotopic composition is considered equivalent to a Low ^{238}Pu Content material for the Nuclear Material Heat Production sub-factor.

Table 2. Proposed Quantification Principle for the Materials Attractiveness Factors

Attractiveness Phase	Acquisition Phase		Processing Phase	Utilization Phase	
Sub-Factor	Overall Net Weight	Radiation Dose Rate	Processing Time and Complexity	Nuclear Material Mass Requirement	Nuclear Material Heat Production
Attractiveness Level	Item Portability	Acute Health Effects	Nuclear Material Concentration	Uranium Isotopics	Plutonium Isotopics
High	Man Portable	Not-Lethal	Pure	Highly (Very Highly) Enriched	Low Heat Output
Medium	Vehicle Portable	N/A	High Grade	Highly (Moderately) Enriched	Moderate Heat Output
Low	Heavy Truck Portable	Lethal[a]	Moderately Diluted[c]	Low Enriched[e]	High Heat Output[g]
Very Low	N/A	Incapacitating[b]	Highly Diluted[d]	Low (Very Low) Enriched[f]	N/A

[a] INFCIRC 225/Rev. 5 standard of greater than 1 Gy/h @ 1 m. Here, 1 Gray (Gy) = 100 rad
[b] To be determined. Probably greater than 10 Gy/h @ 1 m.
[c] To be determined. Probably less than 10%, but could be as high as about 25% nuclear material.
[d] To be determined. Probably less than 0.1%, but could be as high as about1% nuclear material.
[e] Plutonium of any isotopics is High attractiveness in Nuclear Material Mass Requirement.
[f] INFCIRC 225/Rev. 5 standard of 10 to 20% ^{235}U.
[g] INFCIRC 225/Rev. 5 standard of less than 10% ^{235}U.
[h] Uranium of any isotopics is High attractiveness in Nuclear Material Heat Production.
[i] INFCIRC 225/Rev. 5 standard of greater than 80% ^{238}Pu.

For the used fuel assemblies considered here, all items are vehicle portable, but not easily man portable. Thus, the used fuel assemblies fall in the range of Medium attractiveness for that attractiveness sub-factor. The radiation dose rate for the used fuel is highly variable and will be a function of the fuel assembly design, initial fuel composition, reactor type, burn-up, and age after discharge. Plutonium in the used fuel is moderately diluted. Thus, the used fuel assemblies fall in the range of Low attractiveness for that sub-factor. The plutonium that is extracted is roughly equivalent in utility for weapons use as very highly enriched uranium and it is a relatively low heat output material. Thus, the used fuel attractiveness for these two sub-factors is High. The overall attractiveness is dominated by the Processing Time and Complexity and the Radiation Dose Rate. The materials attractiveness for each sub-factor of the used fuels considered here are summarized in **Table 3**.

Table 3. Attractiveness for Used Fuel Assemblies

Acquisition Phase		Processing Phase	Utilization Phase		Overall Attractiveness
Overall Net Weight – Item Portability	Radiation Dose Rate – Acute Health Effects	Processing Time and Complexity	Nuclear Material Mass Requirement (U)	Nuclear Material Heat Production (Pu)	
Vehicle Portable	Variable	Moderately Diluted	Highly (Very Highly) Enriched	Low Heat Output	Low or Very Low

Considering all five sub-factors, the used fuel will be Very Low in overall material attractiveness if the Radiation Dose Rate is Incapacitating and it will be Low in overall material attractiveness if the Radiation Dose Rate is not-Incapacitating. Even if the Radiation Dose Rate of the used fuel is not-Lethal, the overall material attractiveness will still be Low because the plutonium in the used fuel is Moderately Diluted. As a result, the materials attractiveness analyses on specific used fuel assemblies need only determine the radiation dose rate to determine whether the overall material attractiveness is Low or Very Low.

APPROACH

Commercial Power Reactors

The attractiveness of used fuel assemblies from existing light water reactors (LWRs) such as the typical BWR 7x7, BWR 8x8, PWR 17x17, PWR-MOX 17x17, and VVER-440 as a function of burn-up and decay time are evaluated. The evaluation assumes that an adversary is willing to sacrifice his life (by exposure to an incapacitating dose rate of 500 rad/h, or 1000 rad/h at 1 m) to obtain the plutonium contained within the used nuclear fuel and it also assumes that the adversary does not have access to shielded transportation and reprocessing facilities. This is a more conservative approach than the spent fuel standard of 100 rad/h at 1 m [5], which is a measure of deterrence to an adversary that is not willing to sacrifice his life to obtain the plutonium contained within the used nuclear fuel. A radiation dose rate of 500 rad/h at 1 m corresponds roughly to a 50% probability of incapacitation of the adversary during an attempted theft of the used fuel assembly. A radiation dose rate of 1,000 rad/h at 1 m corresponds roughly to a 100% probability of incapacitation of the adversary during an attempted theft of the used fuel assembly. This assumes a standoff distance of 30 cm (not 1 m) and a task time of about 20 minutes.

In general, the spent fuel assemblies containing more fuel and or higher burn-up result in larger doses due to the greater quantities of fission products present. Except for the BWR 7x7 and some of the PWR 17x17, these are the same fuel compositions and assembly designs that were assumed in the study previously conducted by Coates and Broadhead [6]. Some key characteristics of each of the fuel types are provided in **Table 2**.

Table 2. Relevant properties and assumptions of the various used fuel assemblies.

Assembly Type	Net Weight (kg)	Initial Enrichment (%)	Burn-up (MWt·d/kg)	Pu (kg)	^{239}Pu (%)
BWR 7x7	256	1.65	6	0.8	85
		2.06	15	1.3	75
		2.97	30	1.6	65
		4.08	45	1.8	60
BWR 8x8	274	1.65	6	0.64	84
		2.06	15	0.99	72
		2.97	30	1.3	62
		4.08	45	1.5	57
PWR 17x17	691	2.23	18	3.4	73
		2.97	30	4.1	65
		4.08	45	4.5	60
		5.24	60	4.7	56
PWR-MOX 17x17	698	4.1†	18	1.5	55
		4.8†	30	1.6	50
		7.18†	45	2.2	49
		9.6†	60	2.8	48
VVER-440	165	2.23	18	0.80	74
		2.97	30	1.0	69
		4.25	45	1.2	66

† (% Pu + Am)/Initial Heavy Metal. Wt % Pu isotopics held constant at: 1.49 ^{238}Pu; 60.53 ^{239}Pu; 25.36 ^{240}Pu; 7.28 ^{241}Pu; 5.34 ^{242}Pu.

Two slightly different approaches were used to obtain the calculated dose rates of the fuel assemblies as a function of burn-up and age. The differences between the two approaches are primarily in the software that was used for the calculations.

In the first approach, the composition of the fuel as a function of burn-up and age was determined using ORIGEN 2.2 [7]. The photon flux was then determined as function of burn-up and age using the T16/BNL [8/9; respectively] libraries of photon source strengths. This source strength was input into MCNPX [10] and the dose rate was calculated at various points 1 m from the assembly face. This approach was applied to the BWR 7x7 and the PWR 17x17 calculations.

In the second approach, the composition of the fuel and photon flux as a function of burn-up and age was determined using ORIGEN-ARP [11]. The calculated photon flux was propagated throughout the assembly using the MAVRIC sequence [12] in the SCALE package [13] to determine the dose rate at 1 m from the face of the assembly. This approach was applied to the BWR 8x8, the PWR-MOX 17x17, and the VVER-440 calculations. Because the BWR 7x7 and 8x8 cases are expected to be similar and the PWR 17x17 and the PWR-MOX 17x17 are expected to be similar, the two approaches can be compared using these cases. The Pu isotopics were held constant for MOX initial fuel charges. The elemental concentration of Pu in the fresh fuel was varied with reference to a nominal value of 7.18% for 44600 MWd/MTHM, as per [14], with MOX compositions based on [15].

Small Modular Reactors (SMRs)

A new generation of small modular reactor (SMR) designs promises a number of benefits relative to the existing fleet of commercial power reactors, including portability, viable initial investment level, scalability due to modularity, and improved security. **Table 4** lists several proposed SMRs by the US and international nuclear reactor vendors which are currently being discussed and may be considered for pre-application review by the USNRC [16].

Table 4. The proposed SMR by the US and international nuclear reactor vendors.

Name (Example)	Power, MWe	Type	Producer
mPower	180	iPWR	Babcock & Wilcox
Westinghouse SMR	225	iPWR	Westinghouse Electric Company
NuScale	45	iPWR	NuScale Power LLC
SMR-160	140	PWR	Holtec International
PBMR	128–165	HTGR	Chinergy (China),
GT-MHR	285	HTGR	General Atomics,
S-PRISM	311	FR	GE Hitachi Nuclear Energy
4S	10	FR	Toshiba - Japan

iPWR – Integrated pressurized water reactor
HTGR – high temperature gas-cooled reactor
FR – fast reactor

Among these proposed SMRs, mPower's integrated PWR (iPWR) had already received funding support from the USDOE's first round funding-opportunity-announcement (FOA). The other two iPWR concepts by Nuscale, and Westinghouse are applying for DOE support in its 2nd FOA. These three iPWR based SMR concepts are mostly ready for the USNRC's design concept certification. These iPWR based SMRs use fuel assemblies of full or somewhat shorter length compared to typical PWR 17x17 fuel assemblies and have similar burnup (MWd/kg) as in existing PWRs. Therefore, the dose rates produced by a used SMR/iPWR fuel assembly should be similar to that produced by a PWR 17x17 fuel assembly.

The mPower SMR/iPWR has a full core refueling every 4 years. Depending on the operating conditions, the fuel assemblies from the periphery of the reactor core may have lower burn-up than those discharged from near the center of the core. Nevertheless, the differences between the proposed SMRs/iPWRs and the existing power reactors largely come down to the differences in fuel assembly size (*i.e.*, net weight) and operating characteristics. **Table 5** shows some specific information of the proposed iPWR based SMRs by the US vendors.

Table 5. The proposed iPWR based SMRs by the US vendors.

Reactor	mPower	Nuscale	Westinghouse
Type, Rating	Integrated PWR 180 MWe	Integrated PWR 45 MWe, 12 modules	Integrated PWR 225 MWe
Vendor/Owner	Babcock & Wilcox, Bechtel, TVA	NuScale Power, Fluor, OSU	Westinghouse, Burns and McDonnell, Ameren Missouri
Module power **# of Modules**	180 1-10	45 12	225 ~5
Underground/ Siting	Yes	Yes Containment immersed in water pool underground	
Fuel/Refueling	Half length PWR 17x17 fuel assembly, Full core discharge at 4 y	Half length PWR 17x17 fuel assembly, Refueling: 1 -2 y	8 ft. long PWR 17x17 fuel assembly, Refueling: 2 y
Approximate Assembly Net Weight (kg)	~350 kg	~350 kg	~470 kg
Used Fuel Storage	Underground	Underground	Similar to AP1000

Dose rates for the three iPWR systems will be roughly the same as the full size PWR 17x17 assemblies. The dose rate at 1 m is dominated by the mid portion of the assembly thus the dose contributed by the ends of the assemblies is negligible. In estimating the dose rate from the iPWR assemblies previous calculations of PWR 17x17 are taken as an approximation [17].

RESULTS

Existing Commercial Power Reactors

The radiation dose rates of used fuels from the following five reactor types as a function of burn-up and cooling time (age) are calculated for the following:

- BWR 7x7 fuel assembly
- Westinghouse PWR 17x17 assembly
- BWR 8x8 fuel assembly
- MOX fuel in a Westinghouse PWR 17x17 assembly
- VVER-440 fuel assembly

The calculated dose rate as a function of burn-up and age is plotted in **Figures 1 and 2**. The dose-rate level below which the used fuel is no longer “self protecting” or “lethal” (*i.e.* ~100 rad/h at 1 m) and two higher dose-rate levels representing “incapacitating” dose rates for time frames of exposure (*i.e.* 500 rad/h and 1000 rad/h at 1 m) are also shown on the plots.

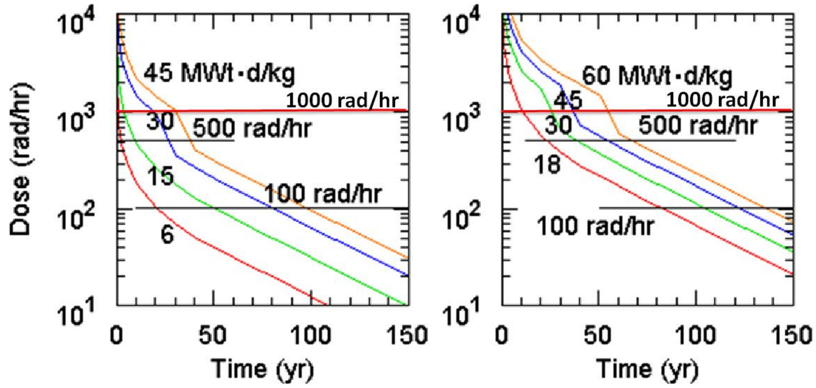

Figure 1. Calculated dose rate as a function of burn-up and age for a BWR 7x7 (left) and a PWR 17x17 (right).

The calculated total dose rate from a BWR 7x7 and PWR 17x17 fuel assembly as a function of burn-up and age is plotted in **Figure 1**. The point at which the used fuel is no longer "self protecting" or "lethal" (*i.e.* ~100 rad/h at 1 m which for high energy photons is the same as ~100 rem/h at 1 m) and the point at which the used fuel is no longer "incapacitating" (*i.e.* ~500 rad/h or ~1,000 rad/h at 1 m) are also shown on the plots. Assuming an "incapacitating" dose rate of 1,000 rad/h at 1 m, **Figure 1 (left)** shows that the used BWR 7x7 assemblies are no longer "incapacitating" between 0.5 and 35 years after discharge from the reactor dependent upon the burn-up. **Figure 1 (right)** shows that used PWR 17x17 assemblies are no longer "incapacitating" between 12 and 55 years after being discharged from the reactor dependent upon the burn-up. When the dose rate from the used fuel is no longer "incapacitating," the overall material attractiveness increases from Very Low to Low.

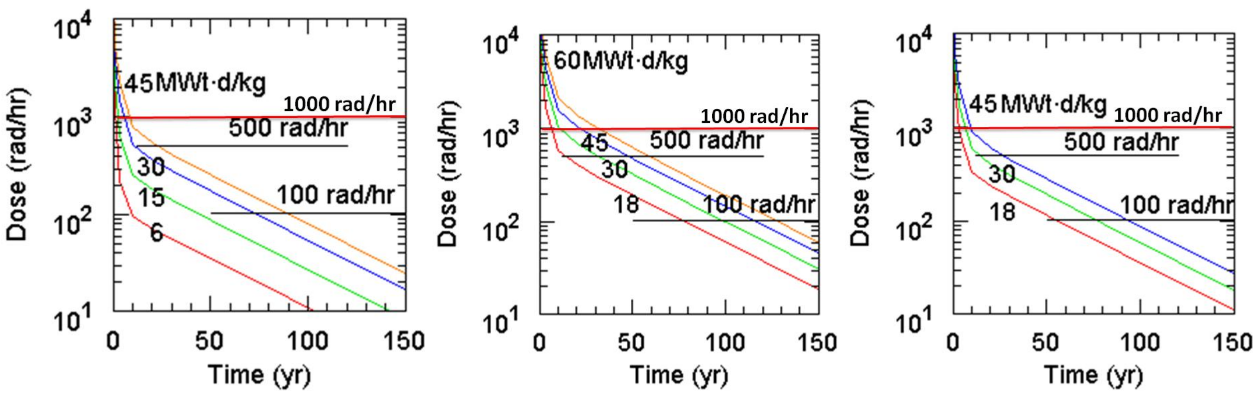

Figure 2. Calculated dose rate as a function of burn-up and age for a BWR 8x8 (left), a PWR-MOX 17x17 (center), and a VVER-440 (right).

The total dose rate from BWR 8x8, PWR-MOX 17x17, and VVER-440 used fuels as a function of burn-up and age are shown in **Figure 2**. Assuming an "incapacitating" dose rate of 1,000 rad/h at 1 m, the BWR 8x8 used fuel assemblies are no longer “incapacitating” between 0.2 and 10 years of aging after discharge. The PWR-MOX 17x17 used fuel assemblies are no longer “incapacitating” between 10 and 35 years after discharge, and the VVER-440 used fuel assemblies are no longer “incapacitating” between 2 and 12 years after discharge. When the dose rate from the used fuel is no longer “incapacitating,” the material attractiveness increases from Very Low to Low.

Proposed Small Modular Reactors (SMRs)

The radiation dose rates of used fuels from the iPWR based SMRs as a function of burn-up and cooling time (age) are similar to those of the existing PWRs, as shown in **Figure 1** (right) and **Figure 2** (center). The iPWR based SMRs may have somewhat shorter fuel lengths, but this is not a significant factor for determining the dose rates at 1 m away from the mid-center of the assembly. **Figure 3** shows previously calculated doses as a function of burn-up and age after discharge for a PWR 17x17 assembly [17]. As expected these curves are similar to those of PWR 17x17 and PWR-MOX 17x17 shown in **Figures 1** and **2**. The curves in **Figure 3** are used to assess dose rate as a function of burn-up and age for the three iPWR SMRs. A more complete analysis is provided in the companion paper that examines SMRs in more depth [18].

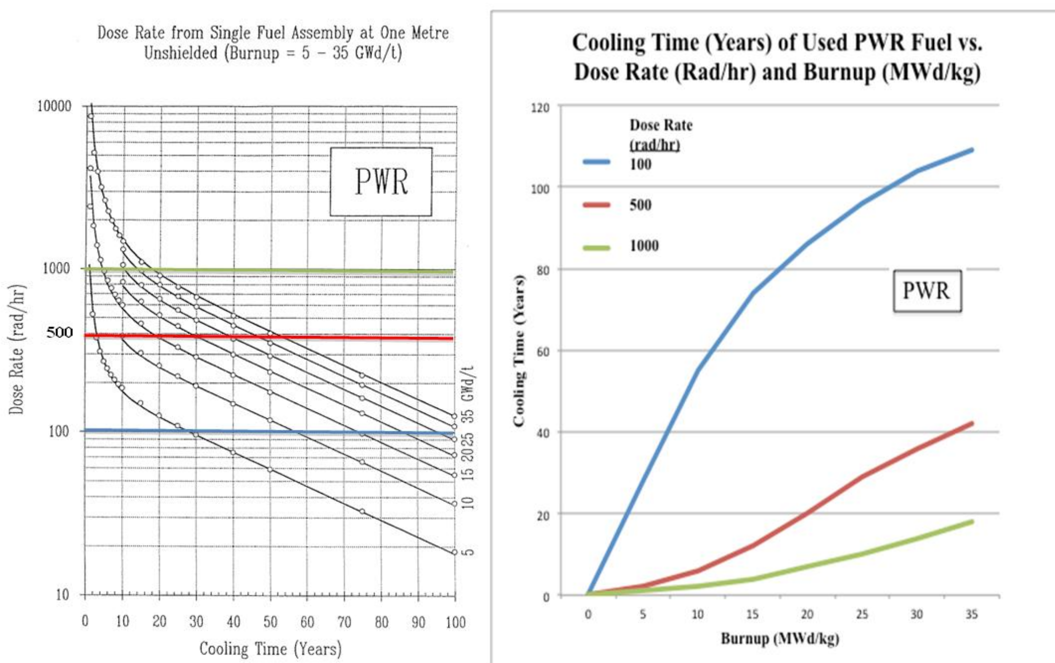

Figure 3. Left: Dose rate as a function of burn-up and age for a iPWR/SMR (represented by a used PWR 17x17 fuel assembly [17]). Right: Cooling time (age) as a function of burn-up for 3 dose rates (100, 500, and 1000 rad/hr).

The cooling time (age) as a function of burn-up for the iPWR based SMRs are calculated for 3 dose-rates: 100, 500, and 1000 rad/hr. The results are plotted and shown in **Figure 3** (right). The 100 rad/hr curve indicates that the time (age) at which the used fuel assembly is no longer providing “lethal” dose rates. While the other two curves (for 500 and 1000 rad/hr) indicate the respective times at which the used fuel assembly is no longer providing “incapacitating” doses for time frames which an adversary may need to complete the illicit tasks (*e.g.*, illegally acquiring the used fuel, and candestinely processing it for weapons purpose). When the dose rate from the used fuel is no longer “incapacitating,” the material attractiveness increases from Very Low to Low.

Commercial Power Reactors versus proposed SMRs

The nuclear material attractiveness of the used fuel from the three proposed iPWR reactors is evaluated and found to be essentially identical to the attractiveness of used fuel from existing commercial power reactors. The cooling times (ages) at which the used fuel is no longer providing an “incapacitating” or “lethal” dose during a time frame which an adversary requires to complete the illicit task are essentially identical for the commercial power reactors and the proposed SMRs. Any differences are due primarily to differences in the burn-up of the fuel. **Table 6** summarizes the times to reach the minimum “lethal” and “incapacitation” dose rate for a range for a nominal burn-up for each reactor type.

Table 6. Summary of ages when spent fuels are no longer providing “lethal” or “incapacitating” radiation dose rates.

Reactor Type	Burn-Up (MWt·d/kg)	Age at which fuel is no longer “lethal” dose rate<100 rad/h (years)	Age at which fuel is no longer “incapacitating” dose rate <500 rad/h (years)	Age at which fuel is no longer providing “incapacitating” dose rate <1000 rad/h (years)
BWR 7x7 and 8x8	6	10-20	1.5-2.3	~0.5
	15	46-50	4-10	1-3
	30	72-80	10-27	6-19
	45	88-98	22-38	10-30
PWR, MOX PWR, and iPWR 17x17	18	76-83	13-23	6-10
	30	98-106	32-46	11-26
	45	115-123	50-54	23-35
	60	127-137	60-67	37-53
VVER-440	18	~53	~7	~3
	30	~75	~19	~6
	45	~92	~25	~10

Other non-PWR SMRs

More detailed analyses of the proposed iPWR and many of the non-PWR SMRs in **Table 4** have been examined in depth in our companion paper [18].

CONCLUSIONS

The nuclear material attractiveness of the used fuel from the three proposed iPWR reactors is for all practical purposed identical to the material attractiveness of used fuel from existing commercial power reactors. The cooling time (age) at which the used fuel is no longer providing an “incapacitating” or “lethal” dose rate is also essentially identical to those of existing commercial power reactors. Any differences in cooling time required for the radiation dose rate to drop below an “incapacitating” level are primarily dependent upon the burn-up of the fuel assembly and have very little dependence upon differences between commercial power reactors and the proposed iPWR SMRs. Even though the proposed iPWR SMRs do not produce used fuel that is more attractive than commercial reactors, this is not necessarily the case for the other non-iPWR SMRs that are under consideration. Any of these non-iPWR SMRs will need further evaluation before any conclusions can be drawn on the attractiveness of the used fuels from these reactors.

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